FABRY–PEROT INTERFEROMETERS

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CAMBRIDGE UNIVERSITY PRESS
Cambridge
New York New Rochelle
Melbourne Sydney

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, NY 10022, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Austalia

First published 1986
First paperback edition 1988 (with corrections)

British Library cataloguing in publication data
Hernandez, G.
Fabry–Perot interferometers.—(Cambridge studies in modern optics; 3)
1. Interferometer
I. Title
535'.4 QC411

Library of Congress cataloguing in publication data
Hernandez, G.
Fabry–Perot interferometers.
Bibliography
Includes indexes.
1. Interferometer. I. Title.
QC411.H47 1986 535".4 85—24307

ISBN 0 521 32238 3 hard covers
ISBN 0 521 36812 X paperback

Transferred to digital printing 2002

Contents

Preface

Introduction

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Bibliography

Glossary

Indexes

Chapter 1

Historical perspective

The present chapter attempts to give a reasonable, but by no means exhaustive, historical development of the multiple beam interferometer known as the Fabry-Perot.

The Fabry-Perot interferometer consists of two parallel flat semi-transparent mirrors separated by a fixed distance. This arrangement is called an etalon (Fabry and Perot, 1897) or interference gauge (Rayleigh, 1906). A monochromatic light wave incident upon an etalon at an arbitrary angle to the normal of the mirror surfaces will undergo multiple reflections within the mirrors. The intensity distribution of the etalon-reflected and etalon-transmitted interfering beams is found to be, because of the circular symmetry of the device, a set of bright concentric rings, or fringes, on a dark background for the transmission case, and a complementary set of dark fringes on a light background for the reflection case. The angular diameter of these fringes is dependent on the spacing between the etalon mirrors and the inverse wavelength (i.e., wavenumber) of the radiation. Thus, the basic function of a Fabry-Perot device is to transform wavelength into an angular displacement; however, in this process, the etalon adds something of its own to the resultant fringes, and this will be discussed in a later section.

The multiple-beam interferometer is a natural outgrowth of the observations of Newton (1730) and Fizeau (1862) of equal-spacing interference phenomena and of Haidinger's (1849) observations of equal-inclination interference phenomena in thin

FIGURE 1.1. Charles Fabry (1867 - 1945). The Bettmann Archive, Inc.

films. The fringes arising from equal spacing and equal inclination are usually called Fizeau and Haidinger fringes, respectively. The investigations of Lummer (1884) on the properties of light upon reflection from plane-parallel glass plates describes the reflection multiple-beam-interferometer, while Bouloch's (1893) report describes the instrument, the theory and experimental use of the transmission multiple-beam-interferometer. A description of Bouloch's device for metrological use was given by Fabry and Perot (1896, 1897). Fabry and his coworkers, in particular Perot and Buisson, fully explored the behavior, characteristics and use of this device to the extent that it is called the Fabry-Perot interferometer. The original contributions of Lummer and Bouloch have not been appreciated fully, and the suggestion by Duffieux (1969) that this device be called the Bouloch-Fabry interferometer has not acquired wide usage.

Although the original intent of Fabry and collaborators was to determine the standard meter in terms of fundamental units, at that time the wavelength of the red cadmium line, the spectroscopic properties of the device were quickly appreciated, described and used (Fabry and Perot, 1898a, 1898b, 1898c, 1899, 1900a, 1900b, 1901a, 1901b, 1901c, 1901d, 1902a, 1902b; Perot and Fabry, 1898a, 1898b, 1898c, 1899a, 1899b, 1900a, 1900b, 1901a, 1901b, 1904a, 1904b, 1904c, 1904d; Fabry, 1904a, 1904b, 1905a, 1905b; Fabry and Buisson, 1908a, 1908b, 1910a, 1910b, 1911, 1914, 1919; Buisson and Fabry, 1908, 1910, 1912, 1913, 1921; Benoit, Fabry and Perot, 1913; Lummer, 1901a). The first published report on the instrument built for Fabry was given by Jobin (1898) and diagrams of the device have been shown by Fabry and Perot (1899) and Benoit, Fabry and Perot (1913). Because of the high spectral resolution of the multiple-beam-interferometer, it was promptly employed in remeasuring the wavelengths of the solar spectrum (Perot and Fabry, 1900b, 1901a, 1904a; Fabry and Perot, 1901b, 1902a, 1902b; Fabry, 1905b; Fabry and Buisson, 1910a, 1910b; Buisson and Fabry, 1910), the wavelengths of the iron arc (Fabry and Perot, 1901b, 1901d, 1902a, 1902b; Pfund, 1908; Fabry and Buisson, 1910a) and rare gases (Buisson and Fabry, 1913; Merrill, 1917; Burns *et al.,* 1918; Meggers, 1921). Other contemporary users of the device were Lummer and Gehrcke (1902), Barnes (1904), Gehrcke (1906), Hamy (1906), Lord Rayleigh (1906, 1908), Pfund (1908), Zeeman (1908), Nagaoka and Takamine (1915), Meissner (1916), Nagaoka (1917), Strutt (later to become Lord Rayleigh, 1919) and Merton (1920). Lord Rayleigh's contribution was to recognize the Fabry-Perot interferometer as a (light) resonating cavity.

About this time, a variant of the Fabry-Perot, based on the Herschel reflection prism, was introduced by Lummer and Gehrcke (1903) and bears the name of these authors. Although this Lummer-Gehrcke plate was a strong contender with the Fabry-Perot (Lummer and Gehrcke, 1904; Perot and Fabry, 1904c; Gehrcke, 1905; Gehrcke and von Baeyer, 1906; Nagaoka and Takamine, 1912; Bogros, 1930), technical difficulties in its construction, as well as its inflexibility, soon placed this device on the shelf of historically interesting optical instruments.

After this aside, we return to the extension of the applicability of the interferometer by Fabry and coworkers. In 1912, Buisson and Fabry made use of this device to test the kinetic theory of gases by detecting the temperature broadening of the emission lines of gases, Doppler broadening, and then measuring the wavelength shift of the bulk motion of the emitters, or Doppler shift (Fabry and Buisson, 1914). Then, they combined the above into the astrophysical measurement of the Doppler shifts and widths in the Orion Nebula (Buisson, Fabry and Bourget, 1914a, 1914b), while at the same time they measured very accurately the wavelengths of the 'nebulium', now known to be lines from the O II $\left({}^4S^0_{3/2} - {}^2D^0_{5/2,3/2} \right)$ forbidden transitions.

Further uses of the Fabry-Perot include measurements of the viscosity effects of air (Fabry and Perot, 1898d), an electrostatic voltmeter (Perot and Fabry, 1898d, 1898e), the Zeeman effect (Zeeman, 1908, Nagaoka and Takamine, 1915), the index of refraction of gases (Meggers and Peters, 1918) and isotopic and fine structure investigations (Nagaoka, 1917; Strutt, 1919; Merton, 1920).

By 1920 the Fabry-Perot was well-entrenched in spectroscopic circles and spreading into other disciplines, such as its first geophysical application in the wavelength determination of the green line of the night sky (Babcock, 1923) at 557.7345 nm and now known to be the $\left({}^1D_2 - {}^1S_0 \right)$ transition of atomic oxygen.

The maturity of the instrument and its varied uses led to the usual mark of approval of extended reviews and books (Fabry, 1923; Childs, 1926; Hansen, 1928; Williams, 1930).

Developments of the late 1920s and 1930s include the measurement and determination of reference wavelengths (Babcock, 1927; Humphreys, 1930, 1931; C.V. Jackson, 1931, 1932, 1933, 1936), and fine structure of emission lines (Houston, 1926, 1927; D.A. Jackson, 1934; D.A. Jackson and Kuhn, 1935, 1936, 1937, 1938a, 1938b) . Some of these investigations required further capabilities than a single-etalon Fabry-Perot interferometer could deliver, thus, the use of two or more interferometers in tandem was introduced (Nagaoka, 1917; Houston, 1927; Gehrcke and Lau, 1927, 1930; Lau, 1930, 1932; Lau and Ritter, 1932; Pauls, 1932). However, note that Perot and Fabry (1899b) had already used a double interferometer, although not as a spectroscopic device. As the capabilities of the Fabry-Perot device were further developed into the realm of line-breadth measurements, the need for a quantitative mathematical expression for a practical Fabry-Perot interferometer became increasingly apparent (Minkowsky and Bruck, 1935a, 1935b, 1935c). Duffieux (1935, 1939) succeeded in this endeavor, and his work can be considered the highlight of this period.

The two-part review by Meissner (1941, 1942) consolidated the spectroscopic aspect of the Fabry-Perot up to that time, and this review, coupled with the appearance of Tolansky's (1947) book on high-resolution instruments, their construction, alignment and care, set the stage for the next advances in the field of high-resolution spectroscopy. The first development was the production of multilayer dielectric coatings (Banning, 1947a, 1947b; Dufour, 1948; and the review by Heavens, 1960) which allows the attainment of high-reflectivity mirrors with small absorption and/or scattering. These mirror coatings are vastly superior to the previously used, mainly silver, mirror coatings, as they allow the use of much higher reflectivities without the concomitant flux losses associated with absorption by metallic coatings. As will be discussed later, the use of higher reflectivity means, other things being equal, higher resolving power, but the price of this advance was to emphasize the surface defects of the substrates where these multilayer coatings are deposited. This lack of complete flatness of the substrates (as well as the distortions introduced by the multilayer coatings) limits the improvements that can be achieved with higher and higher reflectivity coatings (Dufour and Picca, 1945; Dufour, 1951). The next advance was made by Jacquinot and Dufour (1948) when they moved away from the previous recording methods used with Fabry-Perot interferometers, namely the human eye and the ever-present photographic plate, into quantum detectors (e.g. photomultipliers). Although the ultimate gains of the Jacquinot and Dufour scheme were the efficient use of light and the higher effective quantum efficiency of the detectors (coupled with their inherent linearity and wide dynamic range), the milestone was the realization and accomplishment by Jacquinot and Dufour of the use of the radial symmetry of the Fabry-Perot and the necessary scanning (and its many varieties) of the instrument in order to take full advantage of quantum detectors. In addition to the above, these authors also developed a criterion for the best performance of the instrument, which is called the luminosity-resolution-product (LRP) criterion. Chabbal (1953) fully developed the LRP criterion for the many varied and sundry uses of the instrument.

The impact of Jacquinot and Dufour's (1948) work slowly reached the field (see, for instance, Barrell, 1949, Candler, 1951, and Kuhn, 1951, where in the last, only a few lines are given to photoelectric recording), but applications soon were suggested (Giacomo, 1952; Armstrong, 1953, 1956; Biondi, 1956). Jacquinot (1954) showed that the Fabry-Perot is a more luminous instrument than either grating or prism instruments at the same conditions. P. Connes (1956) further showed that the luminosity of the Fabry-Perot could be increased with his spherical Fabry-Perot, i.e., a compensated instrument. This gain in luminosity is most useful at very high resolving powers where the normal Fabry-Perot starts showing the effects of its limited practical size and fixed LRP. As mentioned earlier, two or more interferometers had been used to increase the the capabilities of a single Fabry-Perot interferometer, and Chabbal (1957, 1958a, b, c) began his studies of multiple etalon devices which eventually led to the very useful PEPSIOS interferometer (Mack *et al.*, 1963). This device is widely used where the highest resolving power coupled with selectivity is required, yet preserving the high luminosity inherent in the Fabry-Perot device.

Tolansky's book (1955), the CRNS Colloquia (1958, 1967), the NPL Symposium (1960) and Jacquinot's review (1960) on interference spectroscopy have served as springboards for most of the recent developments in the field. Besides the PEPSIOS device previously mentioned, we find the proposal to use the Fabry-Perot as the cavity for an optical maser (Dicke, 1958; Prokhorov, 1958; Schawlow and Townes,1958) culminating with the first laser (Maiman, 1960), photoelectric spatial scanning (Armstrong, 1958; Bradley, 1962a; Shepherd *et al.*, 1965; Hirschberg and Platz, 1965; Katzenstein, 1965; Shepherd and Paffrath, 1967; Hirschberg and Cooke, 1970; Hirschberg and Fried, 1970; Hirschberg *et al.*, 1971), dynamic alignment (Ramsay, 1962, 1966; Gadsden and Williams, 1966; Hernandez and Mills, 1973), and the use of insect-eye lenses (Courtès *et al.*, 1966; Courtès and Georgelin, 1967). The 1939 Duffieux approach to the analytical description of a Fabry-Perot interferometer was continued by Krebs and Sauer (1953), Bayer-Helms (1963a, 1963b, 1963c, 1963d, 1964a, 1964b), Tako and Ohi (1965), Del Piano and Quesada (1965), Ballik (1966), Best (1967) and these results have been extended and collected by Hernandez (1966, 1970). The classical treatment of active material in the etalon cavity (Kastler, 1962), illustrates the hitherto unexplored capabilities of the Fabry-Perot. The reviews of Girard and Jacquinot (1967), Herriott (1967), Steel (1967), Shepherd (1967, 1969a, b, 1972), Vaughan (1967), Jacquinot (1969), Koppelmann (1969) and Dyson (1970) show in great detail the contemporary status of high resolution spectroscopy, as well as geophysical and astrophysical applications. In the following years there was a consolidation of techniques and applications in varied fields and the highlights are extension of measurements into the near (Chantrel *et al.*, 1964) and vacuum ultraviolet (Abjean and Johannin-Gilles, 1970; Guern *et al.*, 1974), the proof that an interference pattern exists even at extremely low photon fluxes (Reynolds *et al.*, 1969; Bozec *et al.*, 1970), the matrix treatment of the instrumental function by Neuhaus and Nylén (1970), and the response of the etalon to rapid changes in optical length (Gerardo *et al.*, 1965; Dangor and Fielding, 1970). Also the deconvolution work of the measured spectra by Roig and collaborators (Roig *et al.*, 1967; Fourcade *et al.*, 1968; Fourcade and Roig, 1969), Cooper (1971), Hays and Roble (1971), the optimization of the instrument by Velichko *et al.* (1971) and Pátek's (1967) book on lasers deserve mention. A new technique for automatic alignment , based on Jones and Richards' (1973) report on capacitive micrometers, was first used by Hicks *et al.* (1974) and is now the basis of the more-commonly used automatic-alignment scheme. The tandem etalon system of Perot and Fabry (1899b) was simplified by the double-passed etalon arrangement (Dufour, 1951; Hariharan and Sen, 1961; Müller and Winkler, 1968). Multi-passing an etalon has been described by Sandercock (1971), and this arrangement is used to great advantage in Raman and Brillouin spectroscopy. The Fabry-Perot has also been used as a comb filter in Raman studies (Barrett and Myers, 1971). The analytical treatment of the Fabry-Perot was extended to the off-axis case (Hernandez, 1974), which includes the behavior of interference filters when they are used to scan a spectrum at low resolving power.

The reviews by Roesler (1974), Fabelinskii and Chistyi (1976), Meaburn (1976) and Genzel and Sakai (1977) are excellent references on the PEPSIOS multi-etalon devices and interferometric techniques. In recent years, studies on the fundamental limitations of the signal, with its inherent noise, in the retrieval of information from Fabry-Perot measurements have been made (Hernandez, 1978, 1979; Jahn *et al.,* 1982), and the results provide an optimum set of operational points based on minimum uncertainty criteria. Thus far, such derivations have been made for the determination of Doppler widths (i.e., temperatures) and shifts.

When quantum detectors are employed, typically only part of the central order of the fringe pattern is utilized and many schemes have been attempted to use a larger fraction of the flux gathered by the Fabry-Perot interferometer. Most of these reported results take advantage of the Fabry-Perot multiple orders by using multi-slit or multi-annular masks based on the original suggestions by Jacquinot and Dufour (1948) (Allard, 1958; Meaburn, 1976; Sipler and Biondi, 1978; Dupoisot and Prat, 1979; Okano *et al.,* 1980), by extension into multiple detectors and/or multiple anode detectors (Shepherd *et al.,* 1965; Chaux *et al.,* 1976, Chaux and Boquillon, 1979; Abreu *et al.,* 1981; Rees *et al.,* 1981a; Killeen *et al.,* 1983) which include television camera tubes (Sivjee *et al.,* 1980), and by multiplexing techniques (Shepherd *et al.,* 1965; Hoey *et al.,* 1970; Hirschberg *et al.,* 1971; Neo and Shepherd, 1972; Shepherd *et al.,* 1978). The radiation-modulation concept of the two-etalon TESS (Hernandez *et al.,* 1981, Hernandez, 1982a) preserves the spectral information in the incoming light and thus the (theoretical) gain in luminosity is very large and dependent on the resolving power. This gain is limited in practice to values less than about 1000-fold.

The range of utilization of the Fabry-Perot has been enlarged into the vacuum ultraviolet down to 138 nm (Bideau-Mehu *et al.,* 1976, 1980), and X-ray operation of the device has been proposed (Steyerl and Steinhauser, 1979). The time-measurement method to determine the Fabry-Perot maxima by Pole and collaborators (1978, 1980) and the matched-etalon camera concept of Young and Clark (1980) deserve mention as some of the newer developments.

At this point, this historical overview should end by referring to the reviews of Heilig and Steudel (1978), Hernandez and Roble (1979), Hernandez (1980), Meriwether (1983), Atherton *et al.* (1981), Pismis (1982) and Stenholm (1984) to provide the reader with an idea of the present status of the use of Fabry-Perot devices in the laboratory, and their applications in geophysics, astronomy and laser spectroscopy, while the reviews of Baker and Walker (1982), Chantry (1982) and

Clarke and Rosenberg (1982) cover the millimeter, microwave and infrared regions.

FIGURE 1.2. A. Perot (1863–1925).